

LARGE WOOD IN RIVERS AND ITS INFLUENCE ON FLOOD HAZARD

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ABSTRACT. *In terms of flood hazard, the presence of large wood (logs, trees, branches and roots) in rivers may aggravate the consequences of flood events. This material may affect infrastructures such as bridges, weirs, etc., especially those intersecting forested mountain rivers. Until recently, a widely accepted practice was to systematically remove wood debris from river channels as a preventive measure. However, studies have shown that this practice may be useless as the material is transported and deposited after each flood and may even not benefit the long term natural balance of the river ecosystem. Therefore, the presence of this woody material in rivers must be managed and included in flood hazard and risk analysis. In this paper we present a comprehensive methodological approach to study the role of large wood in rivers, with a focus on flood hazard. First, to understand the dynamics of wood recruitment, the contributing areas delivering wood to the streams have to be delineated and the recruitment mechanisms studied. Thus, an estimate can be obtained of the potential volume of deliverable wood. To analyse wood transport we present a numerical model, which allows simulates the behaviour of individual pieces of wood together with hydrodynamics. Finally, we analyse the impact of wood on the magnitude of flood events (in terms of water level, flow velocity or flooded areas), using as an example a flood which occurred in December 1997 in the Sierra de Gredos. The results allowed us to reproduce the wood deposit patterns during the event and to reconstruct the bridge blockage. This caused the upstream water level to rise by up to 2 meters and reduced the flow velocity, which favoured debris and sediment deposits. Consequently, the effects of flooding were equivalent to those of a greater magnitude event. This increase in the flood hazard has been numerically quantified.*

El material leñoso en los ríos y su influencia en la peligrosidad por inundación

RESUMEN. *Desde un punto de vista de la peligrosidad durante inundaciones, la presencia de restos de vegetación en los ríos (truncos, o árboles completos, ramas y*

raíces: detritos leñosos) puede agravar las consecuencias de dichos eventos. Este material puede afectar especialmente a las infraestructuras como drenajes, puentes, etc. que intersectan ríos en cuencas forestadas montañosas. Una práctica muy extendida y aceptada hasta hace pocos años, es la extracción de este material leñoso de los cauces como medida de prevención. Sin embargo, se ha demostrado que esta práctica puede resultar inútil (el material es transportado y depositado tras cada inundación) e incluso no beneficioso para el equilibrio natural del sistema fluvial a largo plazo. Por lo tanto, es necesario gestionar la presencia de este material leñoso en los ríos, e integrar su estudio en los análisis de peligrosidad y riesgo por inundación. En este trabajo, se presenta una síntesis metodológica integral para estudiar la carga de detritos leñosos en ríos. En primer lugar, para conocer la dinámica de incorporación de este material es necesario establecer las áreas contribuyentes que pueden aportar el material a los cursos de agua y los mecanismos de incorporación. De este modo, es posible estimar el volumen de madera potencialmente disponible. Con el fin de analizar su transporte se presenta un modelo numérico, que permite la simulación del transporte de carga leñosa junto con la hidrodinámica. Asimismo, se analiza la incidencia de la carga en la magnitud de eventos de inundación (calados, velocidades...), presentando como ejemplo la avenida ocurrida en diciembre de 1997 en la Sierra de Gredos. Los resultados obtenidos permitieron reproducir el patrón de depósitos de material leñoso durante el evento y reconstruir cuantitativamente el porcentaje de obstrucción de un puente. Este proceso generó un aumento del calado de hasta 2 metros aguas arriba y una reducción de la velocidad de la corriente, lo que a su vez favoreció el depósito de sedimento y más detritos. Como consecuencia los efectos de la inundación fueron equivalentes a los de un evento de mayor magnitud, siendo este incremento de la peligrosidad cuantificable numéricamente.

Key words: large wood, woody debris, flash flood, flood hazard, flood risk.

Palabras clave: detritos leñosos, material leñoso, avenida, inundación, peligrosidad, riesgo.

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1. Introduction

The high potential risk associated with flash floods in mountain watercourses is a result of a rapid and complex hydrological catchment response. Besides high water levels in the drainage network, important geomorphic changes and the transport of large quantities of wood material must be considered as additional factors in forested areas. Interaction between vegetation and geomorphologic processes in these mountain streams is therefore heightened by abundant wood, high stream power and high sediment transport rates (Johnson *et al.*, 2000; Stoffel and Wilford, 2012). The effects of changing

morphology during flood events and the reduction of cross-sectional areas that are blocked by transported materials such as large wood may increase associated flood risk.

In some of the most important recent flood events in several mountain regions in Central Europe (Italy, Austria, Switzerland), the effect of wood on flood hazard was decisive. The effect was mainly the reduction of the cross-sectional area due to blockage by significant wood transport. This triggered a quick succession of backwater effects with bed aggradation, channel avulsion and local scouring processes that ultimately caused embankment/bridge collapse and floodplain inundations (Diehl, 1997; Lyn *et al.*, 2007; Comiti *et al.*, 2006, 2008; Mao and Comiti, 2010; Lucia *et al.*, 2014). As a result, the flooded areas may be different from those predicted in the absence of wood (Ruiz-Villanueva *et al.*, 2013a) and wood can cause damage to infrastructures or aggravate pier scour (Lyn *et al.*, 2003).

Recent floods in Spain have also highlighted some of these effects caused by large wood, particularly at critical sections such as bridges. Fig. 1 shows pictures of two of the most recent examples, where partially clogged bridges over the Seco River (Teruel, August 2013) and over the Nalón River (Asturias, 2012) can be seen. Although studies have been carried out to identify the role of wood in some rivers (Díez *et al.*, 2001), large wood (LW) material has so far not been generally considered in flood analysis in Spain.



Figure 1. Partially clogged bridges with large wood and drift material crossing the Rivers
 (A) Seco (Teruel), after the August 2013 flood (source: ABC online newspaper);
 (B) Nalón (Asturias), after the 2012 flood (source: La Nueva España online newspaper);
 (C) Cabrera (Ávila) after the 1997 flood (this event is described in the text).

A common management response is to remove LW from the channel (Bradley *et al.*, 2005). This practice is widespread in Spain. This is usually defined as “cleaning” or clearing of rivers and includes the elimination or removal of sediments, living vegetation and dead wood from the channels. In natural conditions, floods are the mechanisms that regulate river environments. However, the presence of infrastructure on the channels, and the progressive alteration of the hydrogeomorphology and land use of banks and floodplains have led to an exponential increase in channel cleaning, which is now the subject of ongoing debate (Correa, 2013; Ollero, 2013).

Extensive literature now exists describing the positive influence of wood on stream ecology (Martin and Benda, 2001; Gippel and White, 2000; Gregory *et al.*, 2003; Kasprak *et al.*, 2011), since wood provides a habitat for fish and riverine species (Carlson *et al.*, 1990; Jackson and Sturm, 2002; Langford *et al.*, 2012 and references within) and regulates water flows and nutrient fluxes (Welty *et al.*, 2002). More

recently, researchers have been focusing on the influence of large wood on geomorphology and river dynamics (Montgomery, 2003; Gurnell, 2012; Wohl, 2013; Le Lay *et al.*, 2013). In addition, wood reintroduction is a method increasingly used in restoration projects to improve the hydrological, morphological, and ecological status of degraded streams and rivers (Kail *et al.*, 2007).

It has also been demonstrated that wood removal may be unsuccessful, in part because of new wood inputs after flood events (Young, 1991; Gippel, 1995; Dudley *et al.*, 1998). Long term wood removal has also been shown to cause irreversible changes in fluvial systems, altering hydrogeomorphic conditions (Brooks *et al.*, 2003). The European Water Framework and Floods Directives (Directives 2000/60/EC and 40/2007) provide a legal framework favouring the good ecological and geomorphological conditions of water courses, and this may lead to conflicts concerning the current management of large wood in Spain. Consequently, if we discard the assumption that LW is the problem, the approach could, for instance, be redefined as the inability of infrastructures to allow large wood to pass (Lassetre and Kondolf, 2012). It is demonstrated that most of the time wood lie relatively stable in the channel and becomes potentially hazardous to human infrastructure only during short and infrequent high-magnitude events (Mao *et al.*, 2013). Therefore, the challenge is to maintain the equilibrium of the good ecological and hydromorphological condition of rivers, and at the same time analyse and manage the potential risks.

The analysis of flood hazard related to large wood requires an integrated concept covering watershed, forest and riparian forest management, maintenance of the water courses and non-structural and administrative measures (Rudolf-Miklau and Hübl, 2010; Mao *et al.*, 2013). A better understanding of LW entrainment, or the process by which woody material is transported to the river, is therefore needed when considering the effects of LW in rivers from an ecological perspective, for analysing geomorphological processes and for flood hazard assessment.

Therefore, in this paper we propose an integrated methodological approach to analyse LW, from the recruitment mechanisms to the related hazards, including LW transport. Besides the theoretical approach, a case study in Central Spain is presented. Finally, the integrated methodology is summarized, in order to incorporate LW analysis into flood risk assessment.

2. How does wood reach the channels? Defining contributing areas and large wood recruitment processes

The rate of LW delivered to streams and the contributing areas and processes have been the subjects of several studies in recent years. Martin and Benda (2001) constructed a LW budget using a proposed quantitative framework to evaluate spatial and temporal controls on LW recruitment rate transport. Two years later, Benda and Sias (2003) evaluated the mass balance of in-stream organic debris making quantitative estimates of wood flux. May and Gresswell (2003) identified wood recruitment and redistribution mechanisms during a retrospective investigation. Bragg and Kershner (2004) analysed reach-scale tree recruitment based on bank erosion and tree fall patterns. Mazzorana *et al.* (2009) proposed a procedure based on empirical indicators to determine the relative

propensity of mountain streams to recruit woody material. At a watershed scale, Kasprak *et al.* (2011) developed a method using LIDAR data to evaluate potential wood recruitment. Mazzorana *et al.* (2011a) also used raster analyses to estimate absolute volumes of recruited material. At a regional scale, Ruiz-Villanueva *et al.* (2014a) presented a method to define areas that may contribute to the delivery of woody material to streams. This method takes into account the importance of different recruitment processes (landslides, fluvial transport and bank erosion during floods), creating reliable scenarios based on process severity and also provides estimates of potential recruitable wood volumes for each scenario. The whole analysis was based on existing hazard maps, available morphometric information derived from DEMs, geological and geomorphological spatial information and forestry inventories and maps. A GIS was used to obtain a spatially distributed analysis of potential LW source areas and estimated wood volumes. Multi-criteria and multi-objective evaluation and fuzzy logic principles were used to define reliable scenarios, classifying areas by their likelihood to recruit wood material based on potential recruitment processes, vegetation resistance and abundance. Fuzzy associative matrices allowed all the available information to be used reliably based on the three defined categories or impact levels. The potentially recruitable wood (as the number of trees that may contribute wood to the channel throughout the basin) can be estimated for each severity scenario using this method. Simplified mathematical expressions were developed to estimate LW rate. For the three main species in any given area the total canopy cover (C_i) is provided. The tree density (expressed as number of trees per area) is called relative density per species (D_i) and is used together with species occupation and canopy cover to estimate the final number of trees in a given area. A_i is the contributing area defined for a specific recruitment process:

$$Vw_i = A_i \cdot C_i \cdot D_i \tag{1}$$

In the delineated source area, the probability of a tree entering the stream may vary (Fig. 2).

This variability was incorporated into the method using the volume correction factor (F_c), which takes into account vegetation resistance and the severity of the recruitment mechanism (Table 1).

Table 1. Fuzzy associative matrices of vegetation resistance and the volume of the correction factor.

Vegetation Resistance		Vegetation stage			
		Mature	Mid-successional	Young	Re-forested (managed)
Species	Conifer	Medium	High	High	High
	Deciduous	Low	Medium	Medium	Medium
	Riparian	Low	Low	Low	Low

Volume correction factor (Fc)		Vegetation Resistance		
		High	Medium	Low
Recruitment Process severity	High	0.5	1	1
	Medium	0.1	0.5	1
	Low	0.1	0.1	0.5

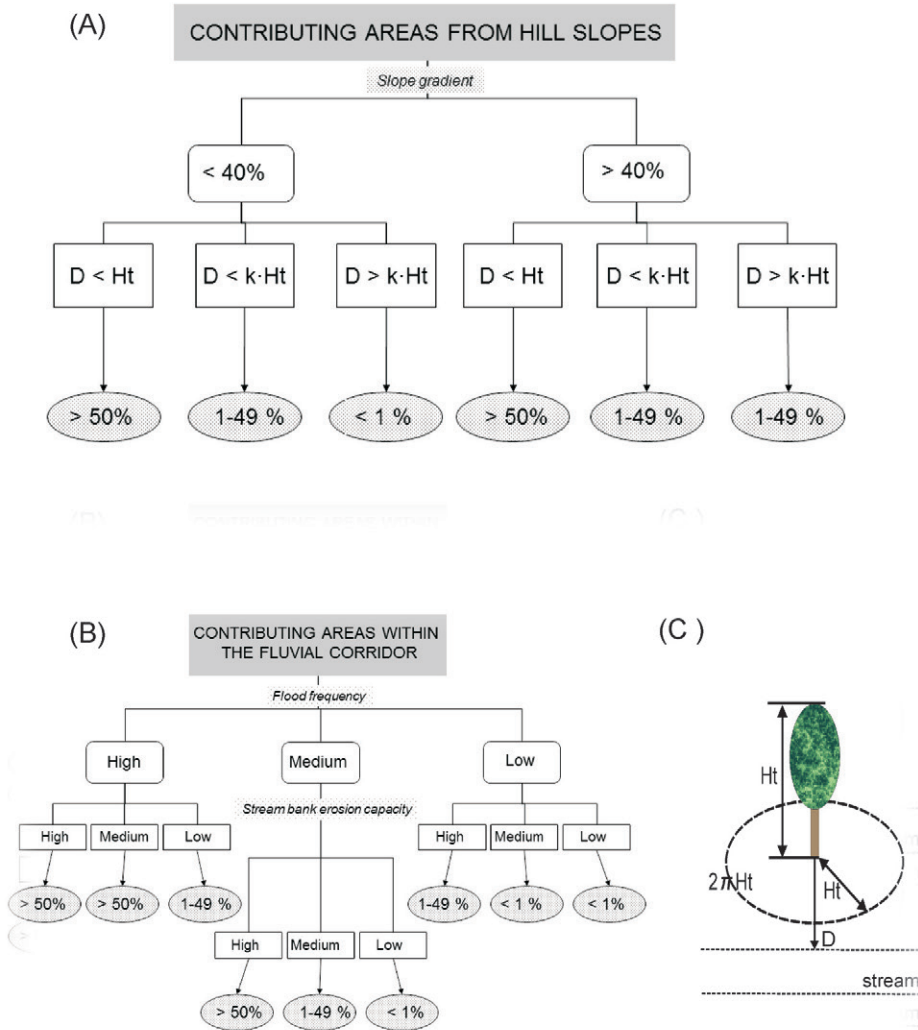


Figure 2. (A) Percentage probability that wood will be recruited from the hillslopes based on connectivity to the channel and slope gradient. D is the distance to the channel, Ht is the tree height and k is the toppling coefficient with a value of 2 assigned here (tree height $\times 2$) (B) Percentage probability of wood being recruited within the fluvial corridor based on flood frequency, flood severity and stream bank erosion capacity. (C) Parameters involved in the probability of a tree entering the stream. Modified from Ruiz-Villanueva et al. (2014).

This volume correction factor is equivalent to a recruitment probability and can be equal to 1, 0.5 or 0.1; here it was computed by means of fuzzy logic matrices (see Ruiz-Villanueva et al., 2014 for details). This correction factor reduces the total

number of trees that could be a source of recruitable wood in those areas where the severity of the process is lowest and/or vegetation resistance highest.

$$Vw_t = Vw_i \cdot Fc \quad (2)$$

Once the number of recruited trees is assessed the number of logs can be estimated, taking into consideration the occurrence of breakage using a coefficient (λ):

$$\text{Logs} = \lambda \cdot Vw_t \quad (3)$$

If λ is equal to 1 this means that there is no breakage and one tree delivers one log to the channel.

This method may be useful as a first step to identify those basins with a high capacity to deliver large amounts of LW and can be used in the preliminary definition of wood loads for physically-based LW modelling. The proposed methodology can also be used for river and forest restoration and management (Hilderbrand *et al.*, 1998). Knowing the spatial patterns of LW recruitment can provide a watershed context for understanding the geomorphic and ecological processes associated with LW (Martin and Benda, 2001). This may help land managers to identify the relative importance of different recruitment processes, knowing where and how much LW is recruited. Forecasts of future conditions could also be simulated using different forestry cover. This allows estimates of changing conditions of source areas and wood volumes in a changing perspective of land use or stand dynamics (Swanson *et al.*, 1998). Scenarios for climate change could also be incorporated. The same is true for predictions based on changing recruitment processes (i.e. types, frequency and severity), so that the recruitment capacity can be analysed at the basin scale.

3. How is wood transported in rivers? A two-dimensional numerical modelling approach

The first works by Braudrick and Grant (2000) and Braudrick *et al.* (2001) provided the basic framework to approach wood mobility. Following this, other studies were carried out to explore wood dynamics in rivers (Haga *et al.*, 2002; Bocchiola *et al.*, 2002, 2006). These studies successfully predicted woody material entrainment based on the balance of hydrodynamic and resistance forces and some of them dealt with transport regimes. Some have used these approaches to describe the mobility of wood in streams (Manners *et al.*, 2007; Curran, 2010), while other experimental attempts focused on the influence of LW on sediment transport and deposit (Svoboda and Russell, 2011; Wallerstein *et al.*, 2001). The transport of wood in rivers can be numerically simulated using a recently developed module for this purpose coupled to a two-dimensional hydraulic model (IBER) based on the finite volume method. The model is described in detail in Ruiz-Villanueva *et al.* (in press). The new module considers wood entrainment and incipient motion performing a balance of the forces acting on each single piece of wood. These forces are: (i) the gravitational force acting on the log, equal to the effective weight of the log in a downstream direction; (ii) the frictional force in the opposite flow

direction, which is equal to the normal force acting on the log multiplied by the coefficient of friction between the wood and the river bed; (iii) and the drag force, also acting in the flow direction, which is the downstream drag exerted on the log by the water in motion (Fig. 3).

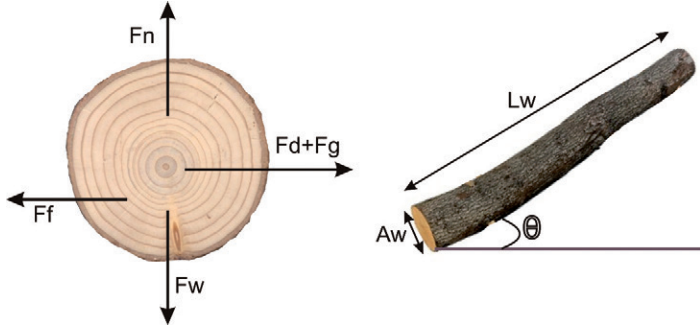


Figure 3. The forces acting on each single piece of wood: F_n is the normal force, F_w is the effective weight, F_f is the frictional force, F_d is the drag force, F_g is the gravitational force, L_w is the length of the log, A_w is the log area perpendicular to the piece length and θ is the angle with respect to the flow.

The combination of these three forces yields the force balance at incipient motion for a circular cylinder lying on the river bed:

$$\begin{aligned} & (g \cdot \rho_w \cdot L_w \cdot A_w - g \cdot \rho \cdot L_w \cdot A_{sub}) \cdot (\mu_{bed} \cdot \cos \alpha - \sin \alpha) \\ & = U_{flow}^2 / 2 \cdot \rho \cdot C_d \cdot (L_w \cdot h \cdot \sin \theta + A_{sub} \cdot \cos \theta) \end{aligned} \quad (4)$$

where L_w is the piece length, ρ_w and ρ are the wood and water densities, respectively, α is the angle of the channel bed in the direction of the flow, g is gravity, A_w is the area of the log perpendicular to the piece length, h is the water depth, C_d is the drag coefficient of the wood in water. Thus, the velocity corresponding to $(F_g + F_d) / F_f = 1$, is called threshold velocity U_{lim} :

$$U_{lim}^2 = \frac{((g \cdot \rho_w \cdot L_w \cdot A_w) - (g \cdot \rho \cdot A_{sub} \cdot L_w)) \cdot (\mu_{bed} \cdot \cos \alpha - \sin \alpha)}{(0.5 \cdot C_d \cdot \rho \cdot (L_w \cdot h \cdot \sin \theta + A_{sub} \cdot \cos \theta))} \quad (5)$$

The velocity for each moving woody log (U_{log}) is estimated as

$$U_{log} = (1 - C^*) \cdot U_{flow} \quad (6)$$

where is a transport inhibition parameter:

$$C^* = U_{lim} / U_{flow} \quad (7)$$

The movement of wood logs includes two possible transport regimes (floating, or sliding and rolling) depending on wood density. When floating, both translation and rotation are considered due to the fact that one end of the piece of wood is moving faster than the other end (based on the flow velocity field), which causes the piece to rotate parallel to the current. The flow velocity at each end (1 or 2) of the log $v^{1,2} = (v_1, v_2)$ is calculated from the flow velocity at the log centre v , the flow velocity gradients and the relative position of the log ends $x^{1,2} = (x_1^{1,2}, x_2^{1,2})$ with respect to the log centre position x :

$$v_i^{1,2} = v_i + \frac{\partial v_i}{\partial x_j} \cdot (x_j^{1,2} - x_j) \quad (8)$$

Interactions between logs and the channel configuration and among logs themselves are also taken into account in the model. Therefore, log velocity and trajectory may change due to contact with the banks or with other logs. If one moving piece of wood meets another piece (floating or resting), the two may collide and continue moving at a different velocity (Fig. 1A). This new velocity (v'_{log}) or final velocity of log i is calculated from the initial velocities ($(v'_{log})^{i,j}$) for both colliding pieces i, j as

$$(v'_{log})^i = (1 + e) \cdot (v_{log})^{cm} - e \cdot (v_{log})^i \quad (9)$$

where

$$(v_{log})^{cm} = \frac{m_i \cdot (v_{log})^i + m_j \cdot (v_{log})^j}{m_i + m_j} \quad (10)$$

v is the velocity of the mass centre of the colliding logs, e is the restitution coefficient (equal to 1 assuming elastic interaction) and m_i and m_j are the log masses.

Moreover, when a piece of wood reaches the bank it can be entrapped, which can reduce the submerged area of the log and the driving forces behind it. The resisting forces are, however, still active around the log and therefore the initial motion condition is recalculated.

The wood jam formation is a 3D process; however, this 2D model attempts to reproduce a quasi-3D process. If a log is lying (resting) on the river bed or bank and another piece floats above it, these two may interact, depending on the water depth and log diameters, and the lying log may start to move or the floating log may stop depending on the force balance.

The hydrodynamics and wood transport are computed in two related ways; thus, the hydrodynamics influence the wood transport, but the presence of wood also influences the hydrodynamics. A drag force is included in the flow model as an additional term in the Saint Venant equations, similar to roughness. This force is

included as an additional shear stress at every finite volume, resulting from the presence of logs.

$$\tau_{wood,i} = \frac{\sum_{logs} F_d}{A_i} \quad (11)$$

where: $\tau_{wood,i}$ is the shear stress at every finite volume, or mesh element, i ; F_d the drag forces; and A_i the volume of the 2D finite volume, or area of mesh element i , that is:

$$\tau_{wood,i} = \left[\sum_{logs} \left(U - U_{log} \right)^2 / 2 \cdot \rho \cdot C_d \cdot (L_w \cdot y \cdot \sin \theta + A_{sub} \cdot \cos \theta) \right] / A_i \quad (12)$$

where U is the water velocity; U_{log} is the component of the log velocity in the direction of the flow. The drag coefficient, C_d , has been analysed extensively before (Manga and Kirchner, 2000). Brooks *et al.* (2006) proposed 1.2 for wood in real streams; and Bocchiola *et al.* (2006) found a value of 1.41 for dowels in flume experiments. In this model, the parameter is assumed to be constant (1.2) but the method allows its value to be changed in each simulation.

The main simplification assumed by the model is the cylindrical shape of the logs, avoiding variations in shape (variations in diameter) and the effect of branches or roots (Braudrick and Grant, 2000). This geometry may not be representative of large wood with complex shapes (Allen and Smith, 2012), but it provides a good approximation of non-rooted and defoliated logs often occurring in rivers as a result of fluvial transport, wood harvesting and forest fires (see Braudrick *et al.*, 1997; Bocchiola *et al.*, 2008; Buxton, 2010; Mazzorana *et al.*, 2011b; Bocchiola, 2011). If branches or roots are present on the logs, then the model presented may not simulate the log movement appropriately.

4. How does large wood influence flood hazard? The 1997 flood in Cabrera Stream

As explained above, as a result of wood transport during floods, flood hazard may be affected (in terms of water level, flow velocity and flooded areas), especially where narrow cross sections and structures such as bridges exist. This was the case during the flash flood which occurred in December 1997 in the Cabrera Stream at the Colonia Venero Claro Bridge (see Fig. 1C and Fig. 4).

The Cabrera Stream is a tributary of the Alberche River in the Tagus River Basin, on the northern slopes of the Sierra de Gredos, in the Spanish Central System. This small poor-gauged forested mountain catchment covers an area of over 15.5 km² with an altitude range of 1168 m (maximum elevation 1923 and minimum 755 m a.s.l.). The main channel is 5500 m long, with an average slope of 21.6%. Heavy rainfall events usually occur in autumn and winter, resulting in abundant surface runoff, sediment mobilization and related flash-flood events.

This event led to a major change in the drainage network pattern, and remobilized large quantities of sediment, damaging the vegetation located within the stream and on the

banks and resulting in a substantial wood recruitment process. Upstream from the point where the Cabrera Stream flows into the Alberche River there is a critical section in the outlet of the catchment; there is a bridge which is the biggest obstacle in the stream and where large deposits of wood and boulders were observed after the 1997 flash flood event (Fig. 5). The evidence from field observations, images and other indicators (e.g. fine sand and coarse wood deposits found on the bridge deck) showed that the bridge was flooded due to the clogged wood. In addition, indirect methods (slope conveyance and competence flow equation) together with hydraulic simulation (using 1D HEC-RAS) and rainfall-runoff modelling (using HEC-HMS) were applied to reconstruct the main flash flood parameters at the bridge section and upstream reach. Peak discharge ($123 \pm 18 \text{ m}^3 \text{ s}^{-1}$), simulated hydrograph, water depth ($\sim 7 \text{ m}$ at the bridge section), blockage ratio ($48 \pm 8\%$ of the bridge section), flow velocity (reach mean $2.85 \text{ m}^3 \text{ s}^{-1}$), and the flood return period ($35 \pm 10 \text{ years}$) were estimated for this event (for details see Ruiz-Villanueva *et al.*, 2013).

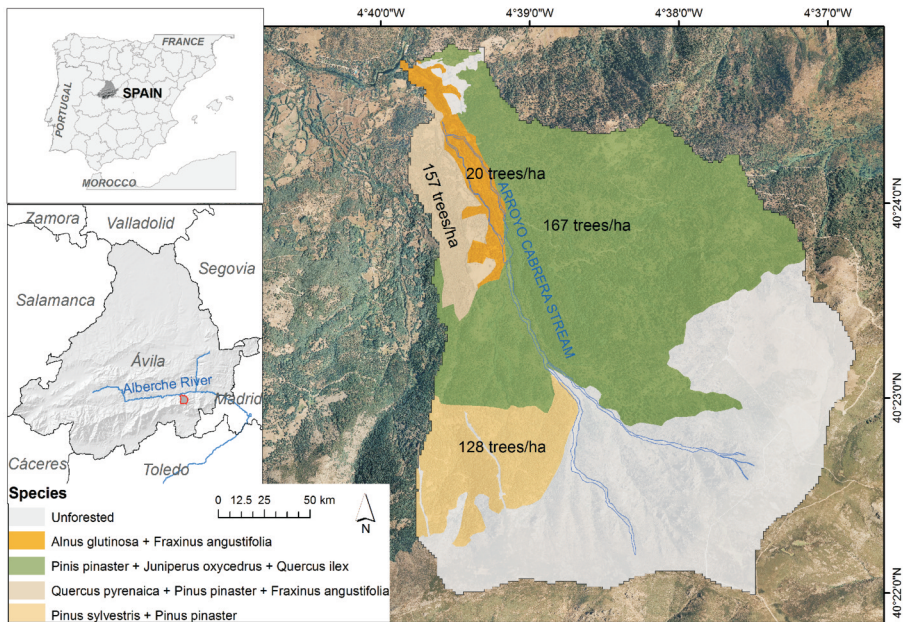


Figure 4. Location of the study site.

In order to analyse the influence of wood on the flood event the procedure applied to the 1997 event study is divided into 3 main stages: (1) estimation of the large wood recruited at a basin scale (analysing the recruitment areas caused by avulsion, fluvial transport and bank erosion occurring during the 1997 event); (2) establishment of the inlet boundary conditions for the studied reach (water and wood fluxes) by means of scenarios; (3) and finally, the modelling of the 1997 flood including large wood transport. This information allowed us to establish the scenario that best reproduces the 1997 event and analyse the linear patterns of predicted wood deposits.

The estimated amount of recruited wood was 186 ± 46 logs. This amount was distributed in time according to three transport scenarios: (i) Scenario 1 (congested transport), 100% of total recruited wood enters just before and during the peak discharge; (ii) Scenario 2 (semi-congested transport), 60% enters before the peak discharge, during the peak this amount is reduced to 30%, and finally during the recession curve 10% of the total recruited wood is transported; (iii) Scenario 3 (steady transport), the total recruited trees enter continuously during the whole event until the middle of the recession curve.

The results of the model reproduce the location of wood deposits and bridge clogging for the three scenarios (Fig. 5).

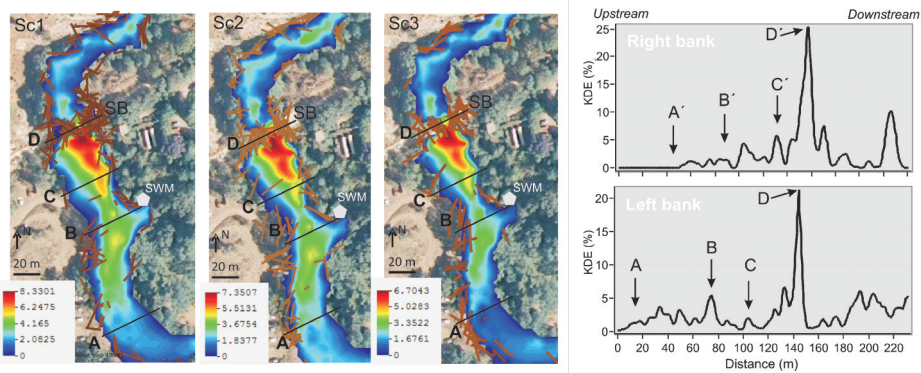


Figure 5. Simulation result for wood deposition patterns. Flow direction from bottom to top. Colour scale shows water depth (m). Average kernel density estimation (%) along the two banks for the three scenarios.

As Fig. 6 shows, the main depositional areas or areas prone to form wood jams are the two bridge abutments (section D, SB), and along the left bank of the stream, particularly the area between sections A and D, and right bank in the area between sections B and D for SC1 and SC2. Since the characteristics of the logs (length, diameter, initial angle) are randomly selected (between established ranges), the final logs forming the deposits may vary for each simulation; however, the depositional areas are approximately the same since they are mainly defined by the topography and hydrodynamics and not only the shape of the logs. Therefore, the mean probability of a log being deposited in a specific place is represented in terms of kernel density estimation (KDE) in Fig. 5 for the combination of the three scenarios. This probability may be equivalent to the probability of woody jam formation for both the left and right banks and can also be used to estimate the probability of a log becoming entrapped in the bridge cross section. This probability for the bridge was up to 30% in SC1, 25% for SC2 and 20% for SC3, 25% in average.

In addition, Fig. 6 shows the main characteristics (water depth and flow velocity) of the flash flood event for 2 scenarios (without wood, and SC2 with wood transport).

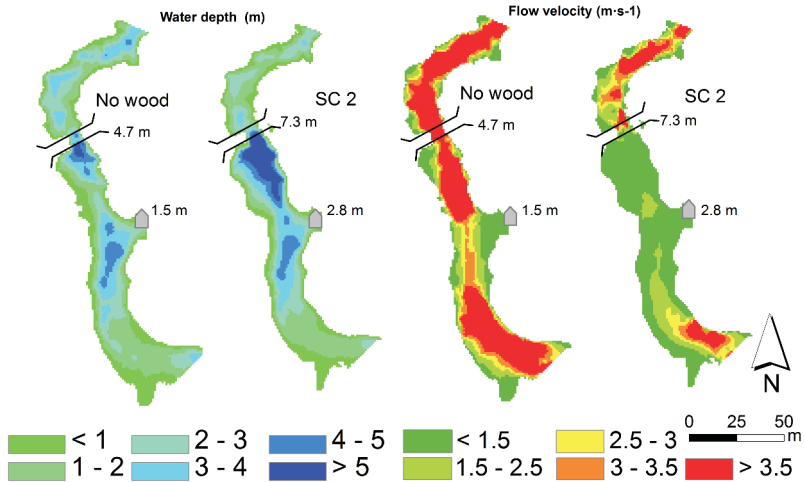


Figure 6. Water depth and flow velocity for the simulated hydrograph without wood, and for SC2. The black line represents the bridge, and the grey polygon is the small white building. The flow direction is from bottom to top.

The water depth for the simulated hydrograph without wood is around 4.7 m at the bridge section; this value is in the same range as that obtained in the previous study (Ruiz-Villanueva *et al.*, 2013), which was around 4.5 m. Although the backwater effect due to bridge clogging increases this level up to 7.1 m according to previous work, 7.3 m was the result obtained in Scenario 2 of this reconstruction. In Scenario 1, this level could increase to more than 8 m (1 m above the bridge deck). Scenario 3 is an intermediate case, where the bridge is less blocked and the water depth does not reach the bridge deck, rising only to 6.8 m. The other high water mark used for the reconstruction was located on the small white building situated on the right bank. This mark was at 2.9 m. Scenario 1 shows a water depth of above 3 m; Scenario 2 gives a value of 2.8 m and Scenario 3 one of 2.3 m.

The main velocity estimated for this event was around 3.5 m s⁻¹ before the bridge obstruction. Although these values are exceeded locally, the main flow velocity agrees with these previous estimates. In addition, as the bridge is increasingly obstructed, it can be observed how the flow velocity decreases upstream.

According to the previous data available for this event, Scenario 2 seems to more closely reproduce the bridge clogging and backwater elevation of the 1997 flood event.

5. Summary and future prospects

A two spatial scale-three step comprehensive methodology is suggested to quantify the effect of the presence/absence and amount of LW in rivers during floods

(Fig. 7). This methodology can be used both retrospectively (to reconstruct a past flood event, such as the one in this study) or to analyse possible scenarios (future floods for different return periods, floods caused by land-use changes, etc.). First, the delivered (or potentially recruitable) LW can be estimated using GIS analysis for delineating and studying the main source areas and recruitment processes by generating scenarios and with the necessary input data. At a local scale (river reach), using the numerical presented model, the transport and deposition of LW can be simulated for the different scenarios. The effects of wood on flood magnitude can then be analysed using probabilistic methods. In addition the model can predict those areas prone to form woody jams, and the clogging probability can be estimated.

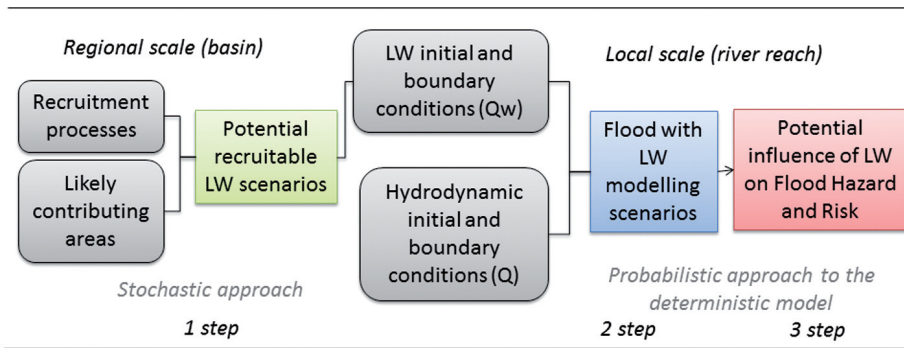


Figure 7. Diagram of the methodology based on a probabilistic approach to numerical modelling, on two spatial scales and in three steps.

The methodological proposal is mainly supported in the numerical model. As usual in numerical modelling some limitations and uncertainties are inherent, since models are just simplifications of reality (Wainwright and Mulligan, 2012). Therefore, in-depth knowledge of the river dynamics, field observations and uncertainty estimations are essential.

6. Conclusions

Large wood transport and deposition should not be discarded from flood analyses (and from river management in general), at least in forested basins. However, the wide spatial and temporal variability associated with wood recruitment coupled with complex transport mechanics may make such analysis particularly challenging. Field data and observations (not always possible) and an in-depth knowledge of the riparian forest and in-stream wood are needed. Numerical models (such as the one presented in this paper) can provide alternative ways of dealing with some of the unknowns regarding wood dynamics. A model represents a controllable virtual world that replicates reality, and allows us to fully analyse any space and time to test hypotheses and run scenarios. These can be used to identify critical sections and design strategies

against flood risk. The most obvious management option is to avoid building any valuable structures in flood-prone areas, however, for infrastructures already located within the fluvial corridor the potential impacts of drift wood transported during floods needs to be carefully analysed.

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